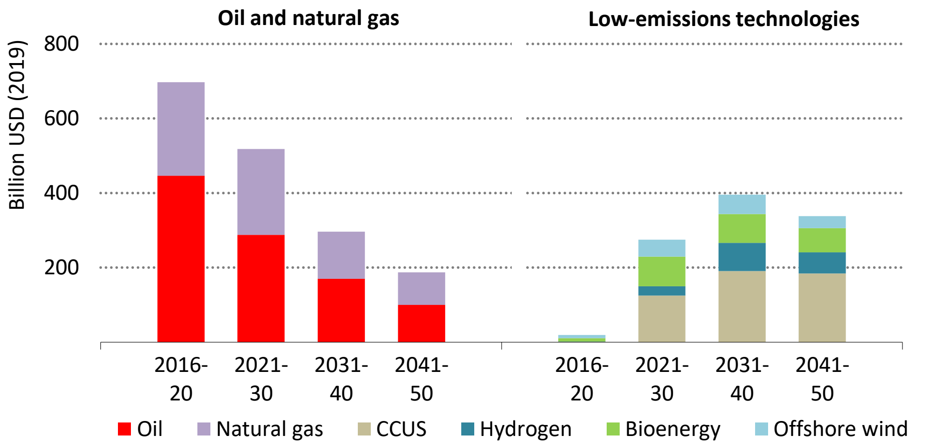
- **Low-emissions hydrogen and hydrogen-based fuels**. Oil and gas companies could contribute to developing and deploying low-emissions hydrogen in several ways (IEA, 2019a). Nearly 40% of hydrogen production in 2050 in the NZE is from natural gas in facilities equipped with CCUS, providing an important opportunity for companies and countries to utilise their natural gas resources in a way that is consistent with net-zero emissions. Of the total output of 530 Mt of hydrogen in 2050, about 30% is processed into ammonia and synthetic fuels (equivalent to around 7.5 mboe/d). The transformation processes involved have many potential synergies with the skills and equipment used in oil and gas processing and refining. Oil and gas companies also have long experience of transporting liquids and gases by pipeline and ships.
- **Advanced biofuels and biomethane**. The production of advanced biofuels grows substantially in the NZE, but this depends critically on continued technological innovation. Many oil and gas companies have active R&D programmes in these areas and could become leading producers. Biomethane – a low-emissions alternative to natural gas – can be produced in large centralised facilities, which could be a good fit with the knowledge and technical expertise of existing gas producers (IEA, 2020d).
- **Offshore wind**. About 40% of the lifetime costs of a standard offshore wind project involve significant synergies with the offshore oil and gas sector (IEA, 2019b). The oil and gas industry has considerable experience of working in offshore locations, which could be of value in the construction of foundations and subsea structures for offshore wind farms, especially when using vessels during installation and operation. The experience of maintaining safety standards in oil and gas companies could also be helpful during maintenance and inspection of offshore wind farms once they are in operation.

Oil and gas companies are well-placed to accelerate the pace of development and deployment of these technologies, and to gain a commercial edge over other companies. In the NZE, investment in low-emissions technologies suited to the skills and expertise of oil and gas companies exceeds that in traditional oil and gas operations by 2030. Total capital spending on these technologies and on traditional oil and gas operations averages USD 650 billion per year over 2021-50, just less than annual investment in oil and gas projects between 2016 and 2020 (Figure 4.7).

Not all oil and gas companies will choose to follow a strategy of diversifying into other types of energy. For example, it is far from certain that national oil companies will be charged by their state owners to diversify and develop low-emissions energy sources outside their core area of activity; other companies may decide simply to concentrate on supplying oil and natural gas as cleanly and efficiently as possible, and to return income to shareholders. What is clear, however, is that no oil and gas company would be unaffected by the NZE and that all parts of the industry need to decide how to respond (IEA, 2020e).

Figure 4.7 ▷ Annual average investment in oil and gas and low-emissions technologies with synergies for the oil and gas industry in the NZE



Investment in low-emissions technologies suited to the skills and expertise of oil and gas companies exceeds investment in traditional operations by 2030

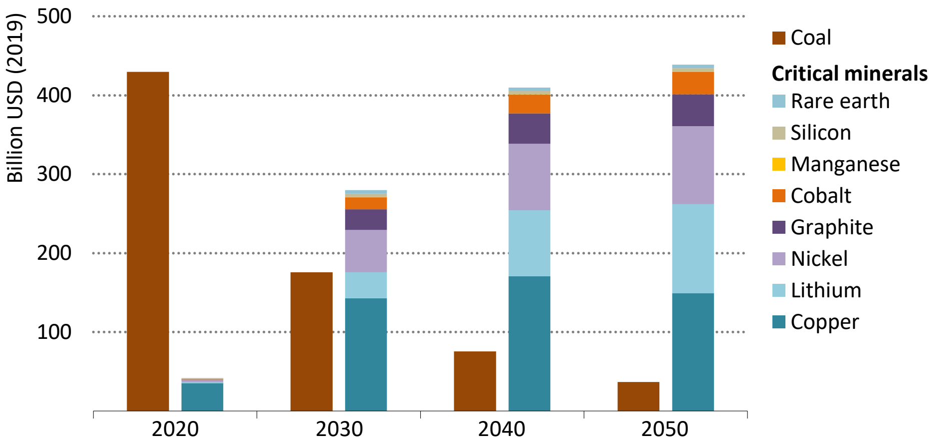
Note: CCUS = carbon capture, utilisation and storage.

4.3.2 Coal

The precipitous decline in coal use projected in the NZE would have major implications for the future of mining companies and countries with large existing production capacities. Around 470 million tonnes of coal equivalent (Mtce) of coal used in the NZE in 2050 is in facilities equipped with CCUS (80% of global coal demand in 2050), which prevents an even sharper decline in demand. But no new coal mines or mine extensions are needed in the NZE. Retraining and regional revitalisation programmes would be essential to reduce the social impact of job losses at the local level and to enable workers and communities to find alternative livelihoods. There could also be opportunities to locate new clean energy facilities, including the new processing facilities that are needed for critical minerals, in the areas most affected by mine closures.

For mining companies, however, the contraction in coal demand in the NZE could be offset by the need to increase mining of other raw minerals, including those vital to many clean energy technologies, such as copper, lithium and nickel (IEA, 2021a). Global demand for these critical minerals rises rapidly in the NZE (Figure 4.8). For example, demand for lithium for use in batteries expands by a factor of 30 by 2030, while demand for rare earths, primarily used for making EV motors and wind turbines, increases by a factor of ten by 2030. Critical mineral resources are not always located in the same locations or countries as existing coal mines, but the skills and experience of mining companies will be essential to ensure that the supply of these minerals is able to match demand at reasonable prices. By the 2040s, the size of the global market for these minerals approaches that for coal today.

Figure 4.8 ▹ Global value of coal and selected critical minerals in the NZE



The market for critical minerals approaches that of coal today in the 2040s

Notes: Includes total revenue for coal and for selected critical minerals used in clean energy technologies. The prices of critical minerals are based on conservative assumptions about cost increases (around a 10%-20% increase from current levels to 2050).

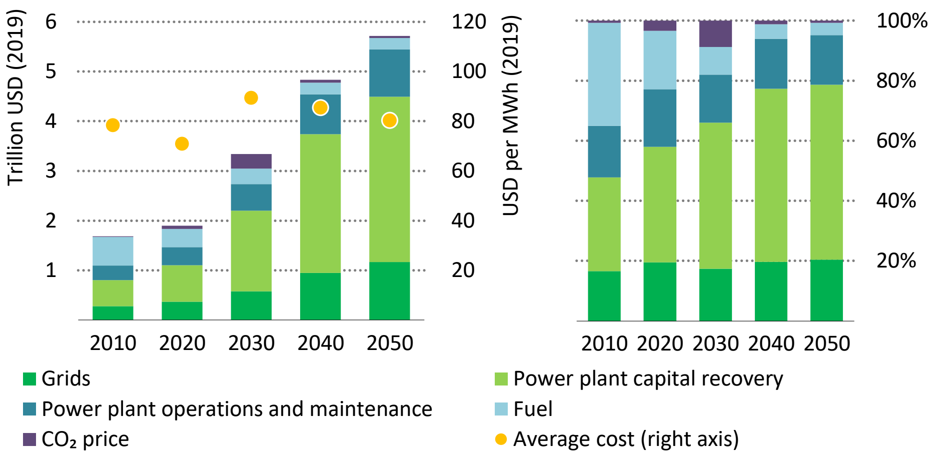
4.3.3 Electricity

Getting to net-zero emissions calls for a massive expansion of the electricity sector to power the needs of a growing global economy, the electrification of end-uses that previously used fossil fuels, and the production of hydrogen from electrolysis. While electricity demand increases more than two-and-a-half times, the rapid transformation of the industry means that total electricity supply costs triple from 2020 to 2050 in the NZE, raising average costs per unit of electricity generation modestly (Figure 4.9).

The electricity supply industry also becomes much more capital intensive, accelerating a recent trend. The share of capital in total costs rises from less than 60% in 2020 (already ten percentage points higher than in 2010) to about 80% in 2050. This is largely due to a massive increase in renewable energy and the corresponding need for more network capacity and sources of flexibility, including battery storage. In the late 2020s and 2030s, the upgrading and replacement of existing solar and wind capacity as they come to the end of their operating lives also boosts capital needs.[6] New nuclear power capacity additions add further capital spending in the NZE. The rising capital intensity of the electricity industry increases the importance of limiting risk for new investment and ensuring sufficient revenues in all years for grid operators to fund rising investment needs – a point underlined by the financial difficulties experienced by some network companies in 2020 due to depressed electricity demand resulting from the Covid-19 crisis (IEA, 2020f).

[6] They typically need replacing after 25-30 years of operation, whereas many conventional hydropower, nuclear and coal plants operate far longer albeit with periodic additional investment.

Figure 4.9 ▷ Global electricity supply costs by component in the NZE



Electricity system costs triple to 2050, raising average supply costs modestly; the massive growth of renewables makes the industry more capital intensive

Notes: Electricity supply costs include all the direct costs to produce and transmit electricity to consumers. Battery storage systems are included in power plant capital recovery.

The rising share of renewables in the electricity generation mix has important implications for the design of electricity markets. When the shares of solar, wind, other variable renewables and nuclear power reach high levels, available electricity supply at no marginal cost is often above electricity demand, resulting in a wholesale price of electricity that is zero or even negative. By 2050, without changes in electricity market design, about 7% of wind and solar output in the NZE would be above and beyond what can be integrated (and so curtailed), and the share of zero-price hours in the year would increase to around 30% in major markets from close to zero today, despite the active use of demand response. If the share of renewables in the electricity generation mix is to rise as envisioned in the NZE, it would therefore be highly desirable to effect significant changes in the design of electricity markets so as to provide signals for investment, including investment in sources of flexibility such as battery storage and dispatchable power plants.

The increase in electricity use inevitably raises associated costs. Operating and maintaining power plants worldwide costs close to USD 1 trillion in 2050 in the NZE, two-and-a-half times the level in 2020. In 2020, upkeep at fossil fuel power plants accounted for USD 150 billion, and renewables required nearly as much, mostly for hydropower. By 2050, the cost of operating and maintaining renewables reaches USD 780 billion, most it needed for wind and solar photovoltaics (PV) as a result of their massive scaling up: offshore wind alone accounts for USD 90 billion.

The sharp reduction of fossil fuel use in the electricity industry and lower fuel prices mean that costs related to fuel and CO_2 prices are significantly reduced. This continues a recent trend driven by near record-low natural gas prices in many markets. Even with rising CO_2 prices over time, the rapid decarbonisation of electricity means that fuel and CO_2 make up a declining share of total costs, falling from about one-quarter in 2020 to 5% in 2050. The balance of fuel costs shifts towards low-emissions sources, mainly nuclear power and bioenergy (including with CCUS), though some still remains related to natural gas and coal used in power plants equipped with CCUS.

One challenge in this context is what to do about the coal-fired power plants in operation. In 2020, over 2 100 gigawatts (GW) of power plants worldwide used coal to produce electricity and heat, and they emitted nearly 30% of all energy-related CO_2 emissions. Options include retrofitting coal-fired power plants with CCUS technologies, co-firing with biomass or ammonia; repurposing coal plants to focus on providing flexibility; and, where feasible, phasing them out. In the NZE, all unabated coal-fired power plants are phased out in advanced economies by 2030 and in emerging market and developing economies by 2040. As a result, emissions from coal-fired power plants fall from 9.8 gigatonnes (Gt) in 2020 to 3.0 Gt in 2030 and to just 0.1 Gt by 2040 (residual emissions from coal with CCUS plants).[7]

Another challenge is related to the scale of capacity retirements envisaged and associated site rehabilitation, starting with coal. The pace of retirement of coal-fired power plants over 2020-50 is nearly triple that of the past decade. Decommissioning at each site can often last a decade and entail significant cost, and may involve closing a mine as well. In some cases, it may be financially attractive to build a renewable energy project on the same site, taking advantage of the grid connection and limiting the cost of rehabilitation. Thousands of natural gas-fired and oil-fired power plants are also retired by 2050, though these sites are often strategically located on the grid and many are likely to be replaced directly with battery storage systems.

The large fleet of ageing nuclear reactors in advanced economies means their decommissioning increases, despite many reactor lifetime extensions. In the NZE, annual average nuclear retirements globally are 60% higher over the next 30 years than in the last decade. Each nuclear decommissioning project can span decades, with costs ranging from several hundred million dollars to well over USD 1 billion for large reactors (NEA, 2016).

4.3.4 Energy-consuming industries

The changes in the NZE would have an enormous impact on industries that manufacture vehicles and their material and component suppliers. Around 95% of all the cars and nearly all of the trucks sold worldwide in 2020 were conventional vehicles with an internal combustion engine. In the NZE, about 60% of global car sales in 2030 are EVs, and 85% of

[7] A CO_2 capture rate of 90% is assumed, though higher rates are technically possible with reduced efficiencies and additional costs (IEA, 2020g).

heavy-duty trucks sold in 2040 are EVs or fuel cell vehicles. In the NZE, vehicle component suppliers and vehicle manufacturers alike retool factories, change designs to incorporate batteries and fuel cells, and adjust supply chains to minimise the lifecycle emissions intensities of vehicles. This provides opportunities to redesign existing parts and manufacturing processes to improve efficiency and lower costs.

The rapid increase in EV sales in the NZE requires an immediate scale up of new supply chains for batteries as well as recharging and low-emissions refuelling infrastructure. In the NZE, battery production capacity increases to more than 6.5 terawatt-hours (TWh) by 2030, compared with less than 0.2 TWh in 2020. Any delay in expanding battery manufacturing capacity would have a detrimental impact on the roll-out of EVs and slow cost reductions for other clean energy technologies that benefit in the NZE from having similar manufacturing processes and know-how (such as fuel cell vehicles and electrolysers).

In aviation and shipping, liquid low-emissions fuels are central to cut emissions. Switching to some of these would have little impact on vessel design: the use of hydrogen-based fuels or biofuels in shipping would only require changes to the motor and fuel system, and bio-kerosene or synthetic kerosene can operate with existing aircraft. New bunkering and refuelling infrastructure are needed in the NZE, however, and the use of these low-emissions fuels also requires new safety and standardisation standards, protocols for permitting, construction and design, as well as international regulation, monitoring, reporting and verification of their production and use.

In heavy industrial sectors – steel, cement and chemicals – most deep emissions reduction technologies are not available on the market today. In the NZE, material producers soon demonstrate near-zero emission processes, aided by government risk-sharing mechanisms, and start to adapt their existing production assets. For multinational companies, this includes developing technology transfer strategies to roll-out processes across plants. International co-operation would help to ensure a level playing field for all. Within countries, efforts focus on industrial hubs in order to accelerate emissions reductions across multiple industrial sectors by promoting economies of scale for new infrastructure (such as CO_2 transport and storage) and supplies of low-emissions energy.

Materials producers work with governments in the NZE to create an international certification system for near-zero emission materials to differentiate them from conventional ones. This would enable buyers of materials such as vehicle manufacturers and construction companies to enter into commercial agreements to purchase near-zero emissions materials at a price premium. In most cases, the premium would result in only a modest impact on the final price of the product price given that materials generally account for a small portion of manufacturing costs (Material Economics, 2019).

4.4 Citizens

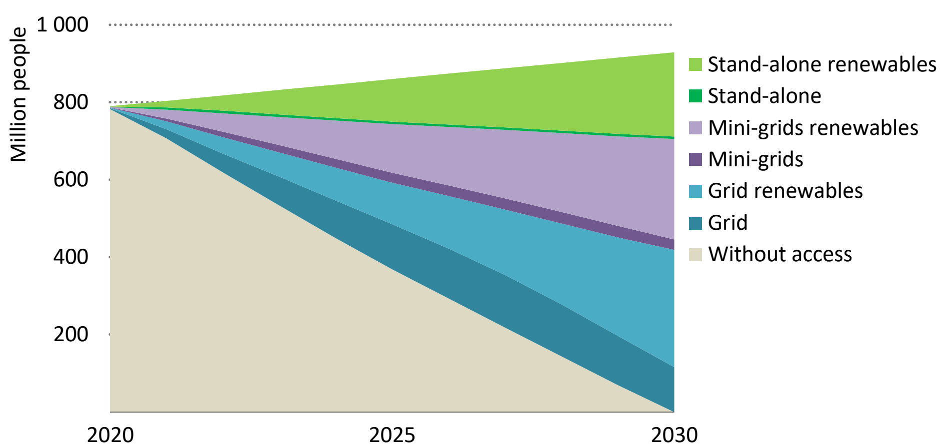
4.4.1 Energy-related Sustainable Development Goals

An inclusive and people-centred transition is key to the world moving rapidly, collectively and consistently toward net-zero emissions by mid-century. The NZE achieves the United Nations energy-related Sustainable Development Goals (SDGs) of universal access to clean modern energy by 2030 (SDG 7.1) and reducing premature deaths caused by air pollution (SDG 3.9). The technologies, options and measures used to achieve full access to low-emissions electricity and clean cooking solutions by 2030 in the NZE also help to reduce greenhouse gas (GHG) emissions from household energy use.

Energy access

About 790 million people worldwide did not have access to electricity in 2020, most of them living in sub-Saharan Africa and developing Asia. Around 2.6 billion people did not have access to clean cooking options: 35% of them were in sub-Saharan Africa, 25% in India and 15% in China. A lack of access to energy not only impedes economic development, but also causes serious harm to health and is a barrier to progress on gender equality and education.[8]

Figure 4.10 ▷ People gaining access to electricity by type of connection in emerging market and developing economies in the NZE



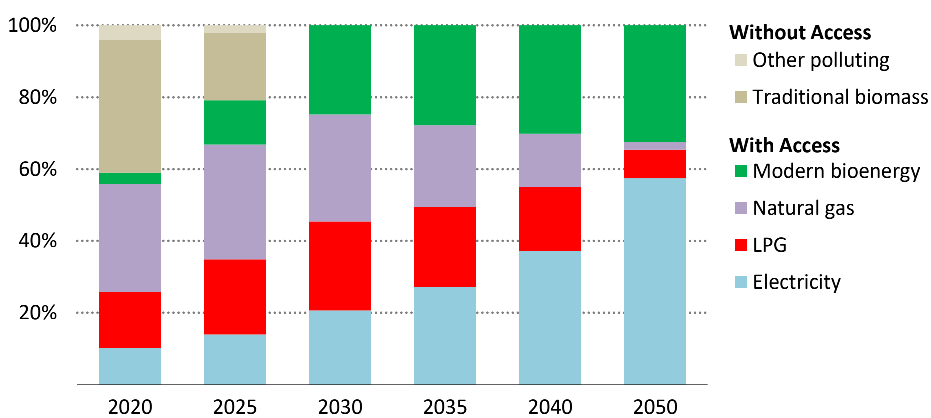
More than 80% of people gaining access to electricity by 2030 are supplied renewable power and just over half via off-grid systems

[8] Households relying on the traditional use of biomass for cooking dedicate around 1.4 hours each day collecting firewood and several hours cooking with inefficient stoves, a burden largely borne by women (IEA, 2017).

Around 45% of those who lack access to electricity by 2030 gain it via a connection to a main grid, while the rest are served by mini-grids (30%) and stand-alone solutions (25%) (Figure 4.10). Almost all off-grid or mini-grid solutions are 100% renewable. Decentralised systems that rely on diesel generators, which are also deployed in some grid-connected systems to compensate for low reliability, are phased out later and replaced with solar storage systems. Achieving full access does not lead to a significant increase in global emissions: in 2030 it adds less than 0.2% to CO_2 emissions. Achieving full access to electricity also brings efficiency gains and accelerates the electrification of appliances, which become critical to emissions reductions in buildings after 2030 in emerging market and developing economies.

For clean cooking, 55% of those gaining access by 2030 in the NZE do so through improved biomass cookstoves (ICS) fuelled by modern biomass, biogas or ethanol, 25% through the use of liquefied petroleum gas (LPG) and 20% via electric cooking solutions (Figure 4.11). LPG is the main fuel adopted in urban areas and ICS is the main option in rural areas. The use of LPG results in a slight increase in CO_2 emissions in 2030 but a net reduction in overall GHG emissions due to reduced methane, nitrous oxides and black carbon emissions from the traditional use of biomass. In addition, LPG is increasingly decarbonised after 2030 using bio-sourced butane and propane (bioLPG) produced sustainably from municipal solid waste (MSW) and other renewable feedstocks. The technical potential of bioLPG production from MSW in 2050 in Africa could be enough to satisfy the cooking needs of more than 750 million people (GLPGP, 2020; Liquid Gas Europe, 2021).

Figure 4.11 ▻ Primary cooking fuel by share of population in emerging market and developing economies in the NZE



Traditional biomass is entirely replaced with modern energy by 2030, mainly in the form of bioenergy and LPG; by 2050, electricity, bioenergy and bioLPG meet most cooking needs

Notes: Modern bioenergy includes improved cook stoves, biogas and ethanol. Liquefied petroleum gas (LPG) includes fossil and renewable fuel.

The achievement of universal access to clean energy by 2030 requires governments and donors to put expanding access at the heart of recovery plans and programmes. There would be multiple benefits: investing heavily in energy access would provide an immediate economic boost, create local jobs and bring durable improvements to social well-being by modernising health services and food chains. In the NZE, around USD 35 billion is spent each year improving access to electricity and almost USD 7 billion each year on clean cooking solutions for people in low-income countries from now to 2030.

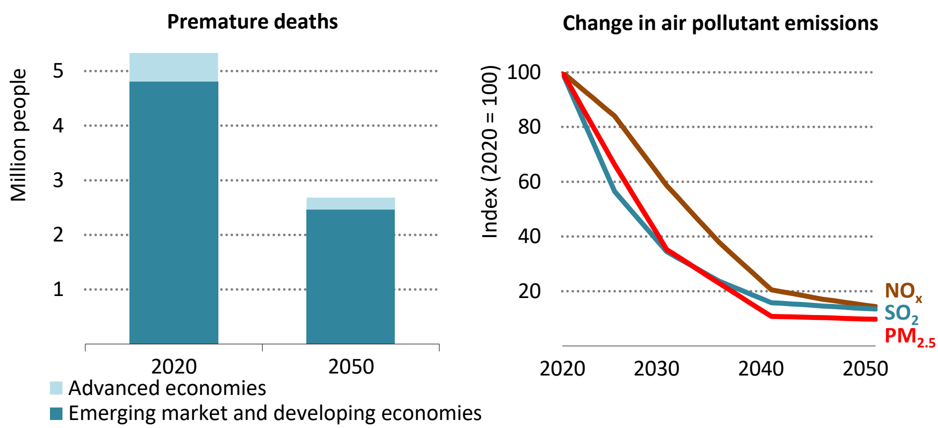
Air pollution and health

More than 90% of people around the world are exposed to polluted air today. Such pollution led to around 5.4 million premature deaths in 2020, undermining economic productivity and placing extra stress on healthcare systems. Most of these deaths were in emerging market and developing economies. Just over half were caused by exposure to outdoor air pollution; the remainder resulted from breathing polluted air indoors, caused mainly by the traditional use of biomass for cooking and heating.

4

Energy-related emissions of the three major air pollutants – sulphur dioxide (SO_2), nitrogen oxides (NO_X) and fine particulate matter ($PM_{2.5}$) – fall rapidly in the NZE. SO_2 emissions fall by 85% between 2020 and 2050, mainly as a result of the large-scale phase-out of coal-fired power plants and industrial facilities. NO_X emissions also drop by around 85% as a result of the increased use of electricity, hydrogen and ammonia in the transport sector. The increased uptake of clean cooking fuels in developing countries, together with air pollution control measures in industry and transport, results in a 90% drop in $PM_{2.5}$ emissions (Figure 4.12). The reduction in air pollution in the NZE leads to roughly a halving in premature deaths in 2050 compared with 2020, saving the lives of about 2 million people per year, around 85% of them in emerging market and developing economies.

Figure 4.12 ▷ Global premature deaths and air pollutant emissions in the NZE



Reductions in major air pollutants mean 2 million fewer premature deaths per year

Sources: IEA analysis based on IIASA.

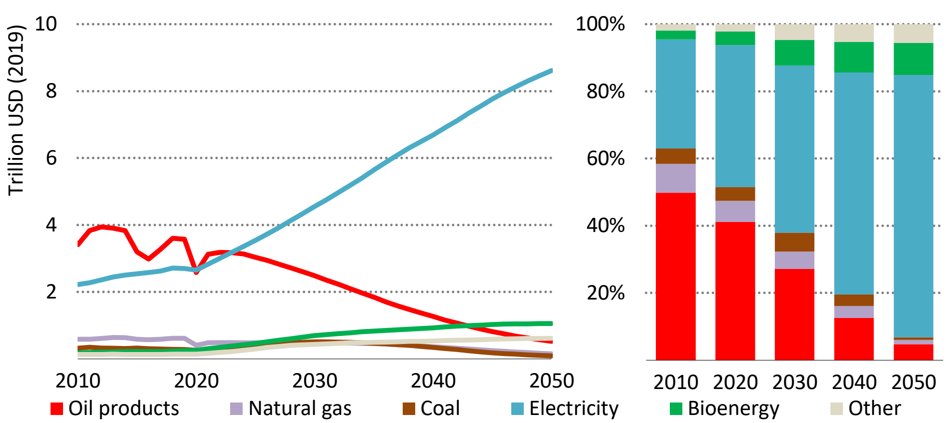
4.4.2 Affordability

Total spending on energy

Energy affordability is a key concern for governments, businesses and households. Global direct spending on energy, i.e. the total fuel bills paid by all end users, which totalled USD 6.3 trillion in 2020, increases by 45% to 2030 and 75% to 2050, in large part reflecting population and GDP growth over this period. As a share of global GDP, the figures look rather different: total direct spending on energy holds steady at around 8% out to 2030 (similar to the average over the last five years), but then declines to 6% in 2050. This decline offsets a significant share of the higher cost of buying new, more efficient energy-consuming equipment.

A portion of the increase in energy spending in the NZE is related to rising CO_2 prices and the removal of consumption subsidies for fossil fuels and electricity. CO_2 pricing (taxes and trading schemes) paid by end users at its peak generates global revenues in the NZE of close to USD 700 billion each year between 2030 and 2035, before declining steadily due to declining overall emissions: these revenues could be recycled into economies or otherwise used to improve consumer welfare, particularly for low-income households. The NZE also sees the progressive removal of consumption subsidies for fossil fuels, many of which disproportionally benefit wealthier segments of the population that use more of the subsidised fuel. Phasing out the subsidies would provide more efficient price signals for consumers, and spur more energy conservation and measures to improve energy efficiency. The impact of phasing out subsidies on lower income households could be offset through direct payment schemes or other means at lower overall costs to the economy.

Figure 4.13 ▷ Global energy spending by fuel in the NZE



Total energy spending increases by 75% to 2050, mainly on electricity

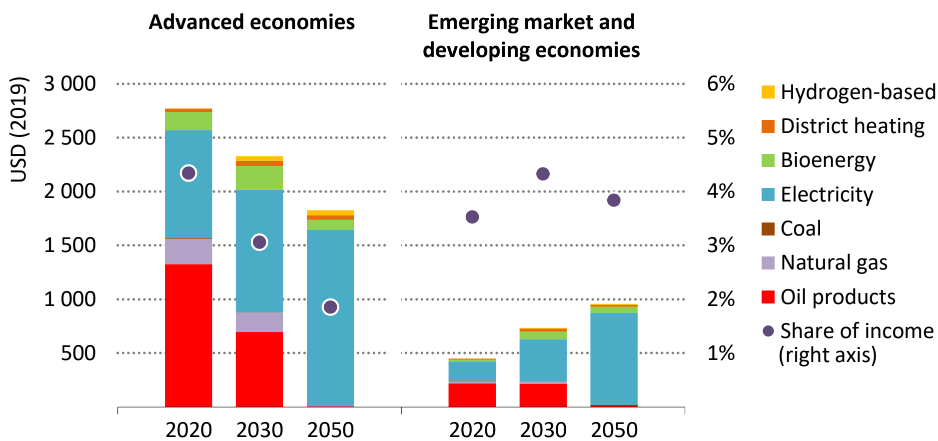
Note: Other = hydrogen-based and synthetic fuels, and district heating.

The transformation of the global energy system in the NZE drives a major shift in the composition of energy spending. Spending on electricity at USD 2.7 trillion in 2020 (45% of total energy spending) exceeded spending on oil products for the first time and it rises to over USD 8.5 trillion in 2050 (80% of total energy spending) (Figure 4.13). Retail electricity prices increase by 50% on average, contributing to the total increase. Spending on oil, which has dominated overall energy spending for decades, goes into long-term decline in the 2020s, its share of spending falling from 40% in 2020 to just 5% in 2050. Spending on natural gas and coal also declines in the long term, offset by higher spending on low-emissions fuels. Spending on bioenergy reaches about USD 900 billion per year by 2040, while other low-emissions fuels, including hydrogen-based products, gain a foothold and establish a market worth of around USD 600 billion per year by 2050.

Household spending on energy

Direct spending by households on energy, including for heating, cooling, electricity and fuel for passenger cars, falls as a share of disposable income in the NZE, though there are large differences between countries (Figure 4.14).

Figure 4.14 ▷ Average annual household energy bill in the NZE



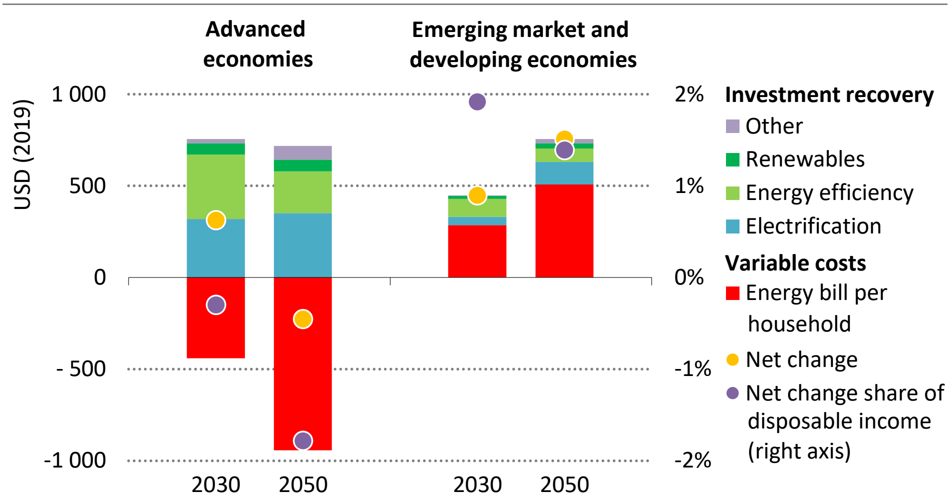
The proportion of disposable household income spent on energy is stable in emerging market and developing economies, and drops substantially in advanced economies

Note: Hydrogen-based includes hydrogen, ammonia and synthetic fuels.

In advanced economies, the average annual bill declines from about USD 2 800 in 2020 to USD 2 300 in 2030, thanks to a strong push on energy efficiency and cost-effective electrification. Oil products make up close to half of household energy bills in 2020, but this falls to 30% in 2030 and almost zero in 2050, due to a rapid shift to EVs and to downward pressure on oil prices. Natural gas bills, which make up almost 10% of the total today, also fall to almost zero in 2050 with the electrification of heating and cooking. Electricity rises from about 35% of household fuel bills in 2020 to 90% in 2050, increasing the sensitivity of households to electricity prices and consumption. Increasing incomes mean that household spending on energy as a share of disposable income drops from 4% in 2020 to 2% in 2050.

In emerging market and developing economies, there is a huge increase in demand for modern energy services linked to expanding populations, economic growth, rising incomes and universal access to electricity and clean cooking options. As in advanced economies, electricity accounts for the vast majority of energy bills in 2050. The use of more efficient appliances and equipment curbs some of the increase in demand, but household bills still increase in the NZE by over 60% to 2030 and more than double by 2050. As a percentage of disposable income, however, bills in emerging market and developing economies remain around 4%, and there are large social and economic benefits from increased energy use.

Figure 4.15 ▷ Change in household spending on energy plus energy-related investment in the NZE relative to 2020



Total household spending on energy increases modestly in emerging market and developing economies, leaving over 90% of additional income available for other uses

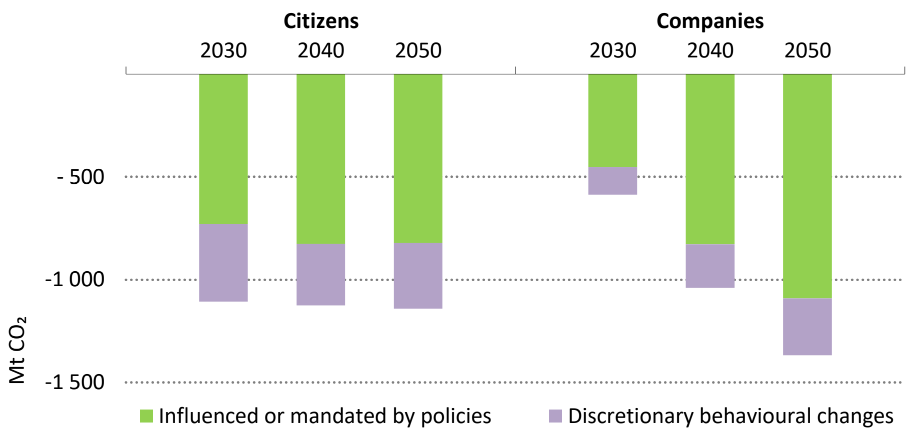
Taking into account additional investment in electricity-consuming equipment such as efficient appliances and electric vehicles, spending on energy plus related investment is USD 1.30 higher per day per household globally in 2050 than in 2020 in the NZE. This modest increase means that expenditure on energy makes up a smaller share of disposable income in 2050 than it does today, though the impacts vary by country. In advanced economies, additional investment in electrification, energy efficiency and renewable energy costs about USD 750 per household by 2030 and USD 720 in 2050, which is fully offset by reductions in the level of energy bills (Figure 4.15). In emerging market and developing economies, a growing basket of energy services means increased use of energy, and total energy-related household spending increases. Additional investment moderates the change in energy bills, with the result that total energy-related spending takes 2 percentage points more of household disposable income in 2030 and 1 percentage point more in 2050 than today.

4.4.3 Behavioural changes

Behavioural changes play an important part in reducing energy demand and emissions in the NZE, especially in sectors where technical options for cutting emissions are limited in 2050. While it is citizens and companies that modify their behaviour, the changes are mostly enabled by the policies and investments made by governments, and in some instances, they are required by laws or regulations. The Covid-19 pandemic has increased general awareness of the potential effectiveness of behavioural changes, such as mask-wearing, and working and schooling at home. The crisis demonstrated that people can make behavioural changes at significant speed and scale if they understand the changes to be justified, and that it is necessary for governments to explain convincingly and to provide clear guidance about what changes are needed and why they are needed.

4

Figure 4.16 ▷ Emissions reductions from policy-driven and discretionary behavioural changes by citizens and companies in the NZE



Three-quarters of the emissions saved by behavioural changes could be directly influenced or mandated by government policies

Around three-quarters of the emissions saved by behavioural changes between 2020 and 2050 in the NZE could be directly influenced or mandated by government policy (Figure 4.16). They include mitigation measures such as phasing out polluting cars from large cities and reducing speed limits on motorways. The other one-quarter involves more discretionary behavioural changes, such as reducing wasteful energy use in homes and offices, though even these types of changes could be promoted through awareness campaigns and other means. Around 10% of emissions savings directly influenced or mandated by government policy would require new or redirected investment in infrastructure. For example, the shift in the NZE from regional flights to high-speed rail would necessitate building around 170 000 kilometres of new track globally by 2050 (a tripling of 2020 levels).

Behavioural changes made by citizens and companies play a roughly equal role in reducing emissions in the NZE. Most changes in road transport and energy-saving in homes would depend on individuals, whereas the private sector has the primary role in reducing energy demand in commercial buildings and pursuing materials efficiency in manufacturing. Companies can also influence behavioural changes indirectly, for example, by promoting the use of public transport by employees that commute or encouraging working from home. However, a simple distinction between the role for individuals and companies masks a complex underlying dynamic: it is ultimately citizens as consumers of energy-related goods and services who shape corporate strategies, but at the same time companies do much to influence and generate consumer demand through marketing and advertising. In the NZE, consumers and companies move together in adopting behavioural changes, with governments setting the direction of those changes and facilitating them via effective and sustained policy support.

The behavioural changes in the NZE happen to different extents in different regions, and reflect a range of geographical and infrastructure constraints, as well as existing behavioural norms and cultural preferences. In countries with low rates of car ownership or energy service demand in buildings, many of the behavioural changes in advanced economies in NZE would not be relevant or appropriate. As a result, around half of the emissions savings from behavioural changes are in emerging market and developing economies, despite around 95% of activity growth in buildings and road transport between 2020 and 2050 occurring there. Nevertheless, there are significant opportunities in emerging market and developing economies for materials efficiency and urban design to decouple growth in economic prosperity and energy services from increases in emissions. For example, around 85% of CO_2 emissions reductions from cement and steel making in 2050 are due to gains in materials efficiency in emerging market and developing economies.

Cities are important to the behavioural changes in the NZE. Urban design can reduce the average city dweller's carbon footprint by up to 60% by shaping lifestyle choices and influencing day-to-day behaviour. For example, compact cities with clustered amenities can shorten average trip lengths; digitalisation can help shared private mobility to become the de facto option to accommodate much of the growth in service demand; and urban green infrastructure can reduce cooling demand (Feyisa, Dons & Meilby, 2014).

4.5 Governments

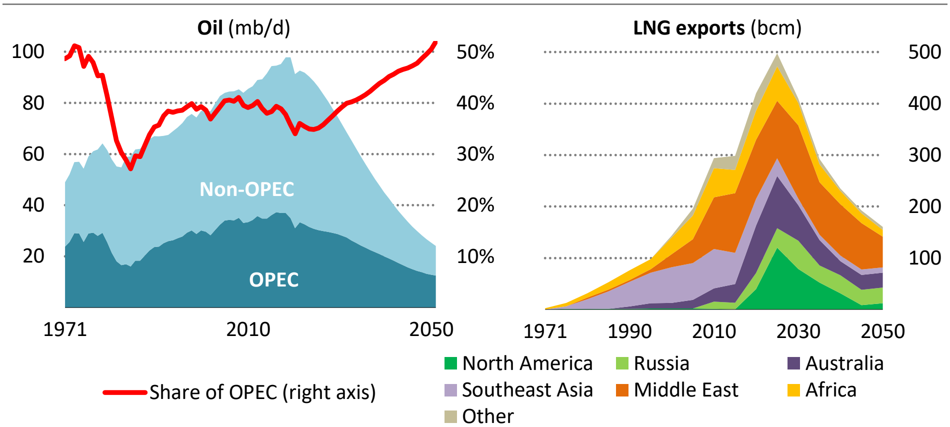
4.5.1 Energy security

Energy security is an important consideration for governments and those they serve, and the pathway to net-zero emissions must take account of it. Concerns about energy security have traditionally been associated with oil and natural gas supplies. The drop in oil and gas demand and the increased diversity of the energy sources used in the NZE may reduce some risks, but they do not disappear. There are also new potential vulnerabilities associated with the need to maintain reliable, flexible and secure electricity systems, and with the increase in demand for raw minerals for clean energy technologies. Improving energy efficiency remains the central measure for increasing energy security – even with rapid growth in low-emissions electricity generation, the safest energy supplies are those that are not needed.

Oil and gas security

No new oil and natural gas fields are required in the NZE beyond those already approved for development, and supplies become increasingly concentrated in a small number of low-cost producers. For oil, OPEC's share of global oil supply grows from around 37% in recent years to 52% in 2050, a level higher than at any point in the history of oil markets (Figure 4.17). For natural gas, inter-regional liquefied natural gas (LNG) trade increases from 420 bcm in 2020 over the next five years but it then falls to around 160 bcm in 2050. Nearly all exports in 2050 come from the lowest cost and lowest emissions producers. This means that the importance of ensuring adequate supplies of oil and natural gas to the smooth functioning of the global energy system would be quantitatively lower in 2050 than today, but it does not suggest that the risk of a shortfall in supply or sudden price rise is necessarily going to diminish, and a shortfall or sudden price rise would still have large repercussions for a number of sectors.

Figure 4.17 ▷ Global oil supply and LNG exports by region in the NZE



Increased reliance on OPEC and other producer economies suffering from falling oil and gas revenues could pose a risk to supply security in consuming countries

Even if the timing and ambition of emission reduction policies are clear, the changes in the NZE clearly have implications for producers and consumers alike. Many producer economies would see oil and gas revenues drop to some of the lowest ever levels (see section 4.2.2). Even if these producers increase their market share, and diversify their economies and sources of tax revenue, they are likely to struggle to finance essential spending at current levels. This could have knock-on effects for social stability, and that in turn could potentially threaten the smooth delivery of oil and gas to consuming countries. Moves on the part of producer economies to gain market share or a failure to maintain upstream operations while managing the extreme strains that would be placed on their fiscal balances could lead to turbulent and volatile markets, greatly complicating the task facing policy makers.

Electricity security

The rapid electrification of all sectors in the NZE, and the associated increase in electricity's share of total final consumption from 20% in 2020 to nearly 50% in 2050, puts electricity even more at the heart of energy security across the world than it already is (IEA, 2020h). Greater reliance on electricity has both positive and negative implications for overall energy security. One advantage for energy-importing countries is that they become more self-sufficient, since a much higher share of electricity supply is based on domestic sources in the NZE than is the case for other fuels. However the increased importance of electricity means that any electricity system disruption would have larger impacts. Electricity infrastructure is often more vulnerable to physical shocks such as extreme weather events than pipelines and underground storage facilities, and climate change is likely to put increasing pressure on electricity systems, for example through more frequent droughts that might decrease the availability of water for hydropower and for cooling at thermal power plants. The resilience of electricity systems needs to be enhanced to mitigate these risks and maintain electricity security, including through more robust contingency planning, with solutions based on digital technologies and physical system hardening (IEA, 2021b).

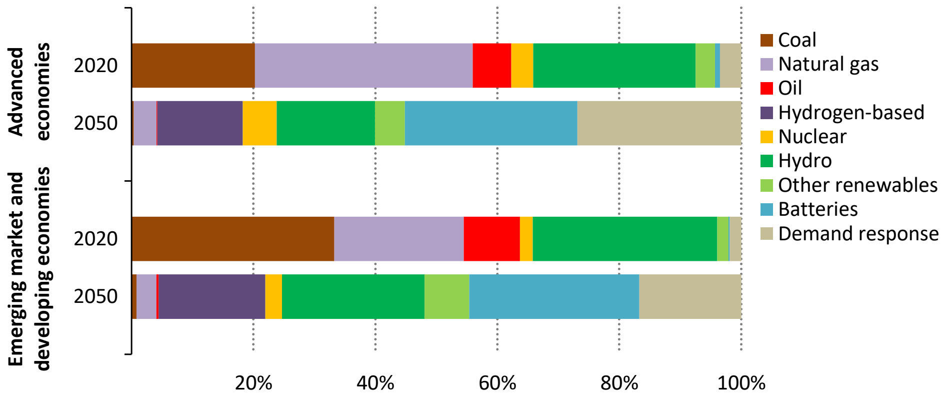
Cybersecurity could pose an even greater risk to electricity security as systems incorporate more digitalised monitoring and controls in a growing number of power plants, electricity network assets and storage facilities. Policy makers have a central part to play in ensuring that the cyber resilience of electricity is enhanced, and there are a number of ways in which they can pursue this (IEA, 2021c).

Maintaining electricity security also requires a range of measures to ensure flexibility, adequacy and reliability at all times. Enhanced electricity system flexibility is of particular importance as the share of variable renewables in the generation mix rises. As a consequence, electricity system flexibility quadruples globally in the NZE in parallel with a more than two-and-a half-fold increase in electricity supply.[9] A portfolio of flexibility sources – including power plants, energy storage and demand response supported by electricity

[9] Electricity system flexibility is quantified here based on hour-to-hour ramping needs, which is only one aspect of flexibility that also includes actions on much shorter time scales to maintain frequency and other ancillary services.

networks – is used to match supply and demand at all times of the year, under varying weather conditions and levels of demand. There is a significant shift in the NZE from using coal- and gas-fired power plants for the provision of flexibility to the use of renewables, hydrogen, battery storage, and demand-side response (Figure 4.18).

Figure 4.18 ▷ Electricity system flexibility by source in the NZE



To meet four-times the amount of hour-to-hour flexibility needs, batteries and demand response step up to become the primary sources of flexibility

Electricity demand also becomes much more flexible as a result of the use of demand response measures, e.g. to shift consumption to times when renewable energy is plentiful. Conventional sources of demand response such as moderating industry activities remain important, but new areas of demand response such as smart charging of EVs unlock valuable new ways of supplementing them.[10] As the EV fleet expands in the NZE, EVs provide a significant portion of total electricity system flexibility. Although the technology already exists, the roll-out of smart charging has been slow to date due to institutional and regulatory barriers; these hurdles are overcome in the NZE. Measures are also implemented to ensure that the digitalisation of charging and other sources of flexibility does not compromise cybersecurity, and that potential social acceptance issues are addressed.

Energy storage also plays an important role in the provision of flexibility in the NZE. The deployment of battery storage systems is already starting to accelerate and to contribute to the management of short-duration flexibility needs, but the massive scale up to 3 100 GW of storage in 2050 (with four hour duration on average) envisaged in the NZE hinges on overcoming current regulatory and market design barriers. Pumped hydropower offers an attractive means of providing flexibility over a matter of hours and days, while hydrogen has

[10] Smart chargers share real-time data with a centralised platform to allow system operators to optimise charging profiles based on how much energy the vehicle needs over a specified span of time, how much is available, the price of wholesale electricity, grid congestion and other parameters.

the potential to play an important part in longer term seasonal storage since it can be stored in converted gas storage facilities that have several orders of magnitude more capacity than battery storage projects.

Dispatchable power is essential to the secure transition of electricity systems, and in the NZE this comes increasingly from low-emissions sources. Hydropower provides a significant part of flexibility in many electricity systems today, and this continues in the future, with particular emphasis on expanding pumped hydro facilities. Nuclear power and geothermal plants, though designed for baseload generation, also provide a degree of flexibility in the NZE, but there are constraints on how much these sources can be expanded. This leaves an important role for thermal power plants that are equipped with carbon capture or use low-emissions fuels. For example, the use of sustainable biomass or low-emissions ammonia in existing coal plants offers a way of allowing these facilities to continue to contribute to flexibility and capacity adequacy, while at the same time reducing CO_2 emissions. Additional measures will also be necessary to maintain power system stability (Box 4.1).

Box 4.1 ▹ Power system stability with high shares of variable renewables

Stability is a key feature of electricity security, allowing systems to remain in balance and withstand disturbances such as sudden generator or grid outages. Historically, conventional generators such as nuclear, hydro and fossil fuels have been central to electricity system stability, providing inertia with rotating machines that allow stored kinetic energy to be instantly converted into power in case of a system disturbance, and generating a voltage signal that helps all generators remain synchronous.

In contrast, newer technologies such as solar PV, wind and batteries are connected to the system through converters. They generally do not contribute to system inertia and are configured as "grid-following" units, synchronising to conventional generators. Maintaining system stability will call for new approaches as the share of converter based resources, and in particular variable renewables, rises much higher in electricity systems.

There is a growing body of knowledge and studies on stability in systems with high shares of variable renewables. For example, a recent joint study by the IEA and RTE, the transmission system operator in France, analyses the conditions under which it would be technically feasible to integrate high shares of variable renewables in France (IEA, 2021d). Based on the findings of this study:

- One option to ensure stability for a net zero power system is to maintain a minimum amount of conventional generation from low-carbon technologies during hours of high shares VRE output. This approach to maintain stability comes at the cost of solar and wind curtailment at high shares.
- Updated grid codes can be used to call for variable renewables and batteries to provide fast frequency response services, which can help reduce the amount of conventional generation needed for stability.

- Synchronous condensers are able to provide inertia without generating electricity. The technology is already proven at GW-scale in Denmark and also in South Australia, but experience needs to be expanded at larger scale.
- Grid-forming converters can allow variable renewables and batteries to generate a voltage signal, though experience with this approach needs to move beyond micro-grids and small islands to large interconnected systems.

Demonstration projects, stakeholder consultations and international collaboration will be critical to fully understand the merits of each of these four approaches and the scope for a portfolio of options that would most cost-effectively achieve net zero emissions while maintaining electricity security.

Electricity networks support and enable the use of all sources of flexibility, balancing demand and supply over large areas. Timely investment in grids to minimise congestion and expand the size of the areas where supply and demand are balanced will be critical to making the best use of solar PV and wind projects, and ensuring affordable and reliable supplies of electricity. Expanding long-distance transmission also makes a key contribution in the NZE, since a lack of available land near demand centres and other factors mean new sources of generation are often located in remote areas. It is important that new transmission systems are built with variable, bidirectional operation in mind in order to maximise the use of available flexibility sources, and that regulatory and market arrangements support flexible connections between systems. The key value of interconnections comes from complementary electricity demand and wind patterns: solar PV output is more highly correlated than wind over large areas.

The NZE sees a major increase in demand for critical minerals such as copper, lithium, nickel, cobalt and rare earth elements that are essential for many clean energy technologies. There are several potential vulnerabilities that could hinder the adequate supply of these minerals and lead to price volatility (IEA, 2021a). Today's production and processing operations for many minerals are highly concentrated in a small number of countries, making supplies vulnerable to political instability, geopolitical risks and possible export restrictions. In many cases, there are also concerns about land-use changes, competition for scarce water resources, corruption and misuse of government resources, fatalities and injuries to workers, and human rights abuses, including the use of child labour. New critical mineral projects can have long lead times, so the rapid increase in demand in the NZE could lead to a mismatch in timing between supply and demand. The international trade and investment regime is key to maintaining reliable mineral supplies, but policy support and international co-ordination will be needed to ensure the application of rigorous environmental and social regulations.

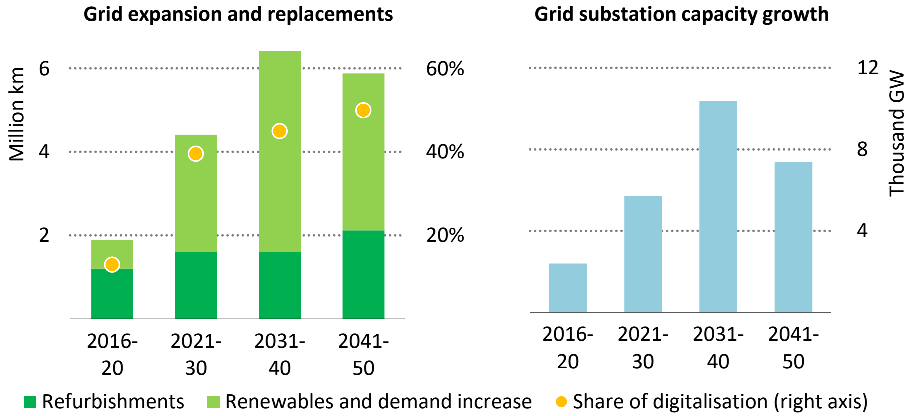
4.5.2 *Infrastructure*

Getting to net-zero emissions will require huge amounts of new infrastructure and lots of modifications to existing assets. Energy infrastructure is transformed in the NZE as all countries and regions move from systems supporting the use of fossil fuels and the distribution of conventionally generated electricity to systems based largely on renewable electricity and low-emissions fuels. In many emerging market and developing economies, the provision of large amounts of infrastructure would be necessary in the coming decades in any case, creating a window of opportunity to support the transition to a net-zero emissions economy. In all countries, governments will play a central role in planning, financing and regulating the development of infrastructure. Some of the main infrastructure components – electricity networks and EV charging, pipelines systems for low-emissions fuels and CO_2, and transport infrastructure – are discussed below.

The rapid increase in electricity demand in the NZE and the transition to renewable energy call for an expansion and modernisation of electricity networks (Figure 4.19). This would require a sharp reversal in the recent trend of declining investment: failure to achieve this would almost certainly make the energy transition for net-zero emissions impossible. Tariff design and permitting procedures also need to be revised to reflect fundamental changes in the provision and uses of electricity. Some of the main considerations include:

- **Long-distance transmission**. Most of the growth in renewables in the NZE comes from centralised sources. Yet the best solar and wind resources are often in remote regions, requiring new transmission connections. Ultra high-voltage direct current systems are likely to play an important role in supporting transmission over long distances.
- **Local distribution**. Energy efficiency gains in households and wider use of rooftop solar PV mean surplus electricity will be available more often, while electric heat pumps and residential EV charging points will require electricity to be more widely available. Together these developments point to the need for substantial increases in distribution network capacity.
- **Grid substations**. The massive expansion of solar PV and wind requires new grid substations: their capacity expands by more than 57 000 GW in the NZE by 2030, doubling current capacity globally.
- **EV charging**. Major new public charging networks are built in the NZE, including in work places, highway service stations and residential complexes, to support EV expansion and long-distance driving on highways.
- **Digitalisation of networks**. With a large increase in the use of connected devices, the digitalisation of grid assets supports more flexible grid operations, better management of variable renewables and more efficient demand response.

Figure 4.19 ▷ Annual average electricity grid expansion, replacement and substation capacity growth in the NZE



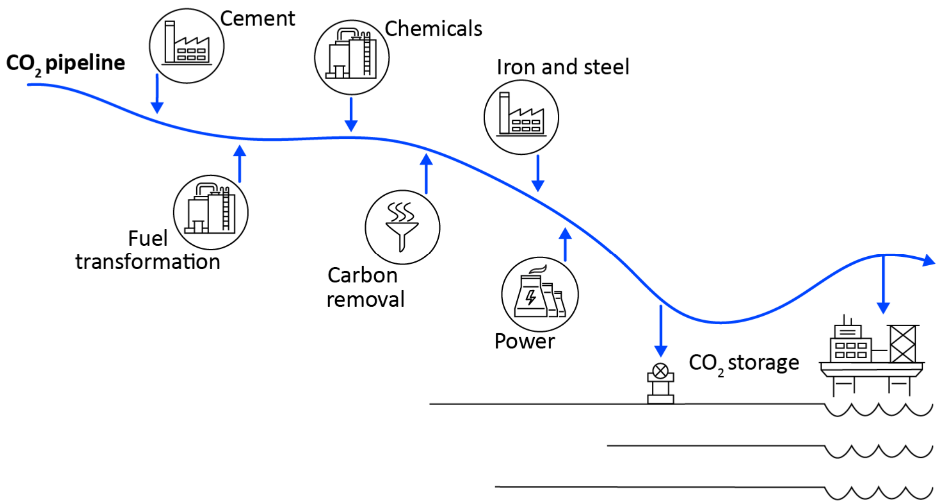
Grid and substation expansion is driven largely by the massive deployment of renewables and electrification of end-uses, with a rising digital share of infrastructure

Note: Substation capacity here assumes active electricity is equal to apparent electricity.

Pipelines continue to play a key role in the transmission and distribution of energy in the NZE:

- Given the rapid decline of fossil fuels, significant investment in new oil and gas pipelines are not needed in the NZE. However investment is needed to link the production of low-emissions liquids and gases with consumption centres, and to convert existing pipelines and associated distribution infrastructure for the use of these low-emissions fuels. Some low-emissions fuels, such as biomethane and synthetic hydrogen-based fuels, can make use of existing infrastructure without any modifications, but pure hydrogen requires a retrofit of existing pipelines. New dedicated hydrogen infrastructure is also needed in the NZE, for example to move hydrogen produced in remote areas with excellent renewable resources to demand centres.
- The expansion of CCUS in the NZE requires investment in CO_2 transport and storage capacity. By 2050, 7.6 Gt of CO_2 is captured worldwide, requiring a large amount of pipeline and shipping infrastructure linking the facilities where CO_2 is captured with storage sites. Industrial clusters, including ports, may offer the best near-term opportunities to build CO_2 pipeline and hydrogen infrastructure, as the various industries in those clusters using the new infrastructure would be able to share the upfront investment needs (Figure 4.20).

Figure 4.20 ▷ Illustrative example of a shared CO_2 pipeline in an industrial cluster



Deployment of technologies like CCUS and hydrogen and their enabling infrastructure would benefit strongly from a cross-sectoral approach in industrial clusters

Transforming transport infrastructure represents both a challenge and an opportunity. The challenge arises from the potential increase in the energy and carbon intensity of economic growth during the infrastructure development phase.[11] Steel and cement are the two main components of virtually all infrastructure projects, but they are also among the most challenging sectors to decarbonise. The opportunity comes from the scope that exists in some countries to develop infrastructure from scratch in a way that is compatible with the net zero goal. Countries undergoing rapid urbanisation today can design and steer new infrastructure development towards higher urban density and high-capacity mass transit in tandem with EV charging and low-emissions fuelling systems.

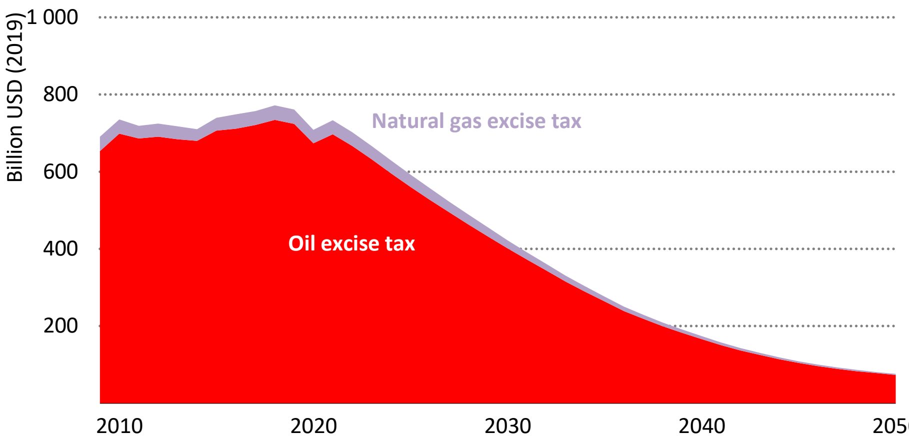
Rail has an important part to play as transport infrastructure is developed. The NZE sees large-scale investment in all regions in high-speed trains to replace both long-distance car driving and short-haul aviation. It also sees large-scale investment in all regions in track, control systems, rolling stock modernisation and combined freight facilities to improve speed and flexibility for just-in-time logistical operations and thus support a shift of freight from road to rail, especially for container traffic.

[11] The modelling for the NZE incorporates the increase in steel and cement that is required to build additional transport infrastructure (roads, cars and trucks) and energy infrastructure, e.g. power plants and wind turbines.

4.5.3 *Tax revenues from retail energy sales*

The slump in the consumption of fossil fuels required to get to net-zero emissions would result in the loss of a large amount of tax revenue in many countries, given that fuels such as oil-based transport fuels and natural gas are often subject to high excise or other special taxes. In recent years, energy-related taxes accounted for around 4% of total government tax revenues in advanced economies on average and 3.5% in emerging market and developing economies, but they provided as much as 10% in some countries (OECD, 2020).

Figure 4.21 ⊳ Global revenues from taxes on retail sales of oil and gas in the NZE



Tax revenues slump from retail sales of oil and gas

Tax revenue from oil and natural gas retail sales falls by close to 90% between 2020 and 2050 in the NZE (Figure 4.21). Governments are likely to need to rely on some combination of other tax revenues and public spending reforms to compensate. Some taxation measures focused on the energy sector could be useful. However, any such taxes would need to be carefully designed to minimise their impact on low-income households, as poorer households spend a higher percentage of their disposable income on electricity and heating. Options for energy-related taxes include:

- **CO_2 prices**. These are introduced in all regions in the NZE, albeit at different levels for countries and sectors, which provide additional revenue streams. The reduction in oil and natural gas excise taxes is more than compensated over the next 15 years by higher revenues from CO_2 prices related to these fuels paid by end users and other sectors, but these too fall as the global energy system moves towards net-zero emissions.
- **Road fees and congestion charges**. These would have the added benefit of discouraging driving and encouraging switching to other less carbon-intensive modes of transport.